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PERSONAL EXPOSURE TO COUGH RELEASED DROPLETS IN QUIESCENT ENVIRONMENT AND VENTILATED SPACES

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Abstract

This study shows the results of an experimental investigation of personal exposure to cough released droplets. Human body is resembled by a thermal manikin with a body shape and surface temperature distribution of a real person. The objective of the study is to examine personal exposure of the manikin exposed to cough released droplets in a calm indoor environment and under uniform air patterns relative to a human body. The findings show that human body orientation relative to the direction and magnitude of invading flow from the surroundings considerably modifies personal exposure. Surrounding uniform flows in most of the scenarios decrease the exposure to cough droplets, however not in all scenarios. Study results show that understanding of the air patterns should be prioritized in ventilation design practice.

Keywords: Personal exposure, Cough, Thermal Manikin, Ventilation flow

1 Introduction

As people spend most of their time indoors, they are constantly exposed to pollution that affects their health, comfort and productivity. In indoor environments that are supplied with low air velocity, heat sources such as occupants play important role in generating air movement. Human body in a state of thermal comfort dissipates 30-35% of metabolic heat by means of convection (Murakami, 2000; Homma and Yakiyama, 1987). Metabolic heat is exchanged with the cooler surrounding air which gives rise to a convective boundary layer (CBL). The CBL accelerates and develops into a human thermal plume above the head after it detaches from the body. Several studies (Lewis et al. 1969; Homma and Yakiyama, 1987; Licina et al. 2014a) have been focused on describing this flow in quiescent environment. Interaction between the CBL and the uniform airflow has been investigated previously (Melikov and Zhou, 1996; Bolashikov et al. 2011). Licina et al. (2014b) investigated interaction between the CBL and three idealized flows (opposing flow from above, transverse flow from front and assisting flow from below). That work provides a basis for the present study that focuses on impact of those idealized flows on personal exposure.

Previous findings have shown that cough expelled droplets become influenced by the typical room airflows at the distance beyond 2 m from the release point due to large velocity drop (Pantelic et al. 2009). How the cough droplets interact with the ventilation flows and subsequently, with the CBL is mostly unknown to date which makes personal exposure predictions challenging. In rooms with mechanical ventilation, the airflow patterns are highly unpredictable and case specific and depend on number of factors (Etheridge and Sandberg, 1996). Most of the studies in the past that involve personal exposure measurements were performed in such case specific environments, hence any generalization of the results is challenging. Due to fragmentation of the previous studies and

their case specific conclusions, general knowledge on how different theoretical airflow patterns and their intensities affect the personal exposure is still missing. In order to derive more general conclusion, there is an obvious need for a simplified approach in which the CBL would be exposed to uniform surrounding airflows (e.g. assisting, opposing and transverse). The objective of this study is to investigate personal exposure to cough released droplets in: (i) quiescent environment; and (ii) exposed to a uniform flow field. The results of this study contribute to the fundamental understanding of the relations between personal exposure and airflow patterns and their intensities.

2 Methods

Measurements were conducted in an environmental chamber with dimensions 11.1 (L) x 8.0 (W) x 2.6 (H) m that was equipped with displacement air distribution system. Four floor standing low-momentum diffusers supplied 100% outdoor air to the chamber that was exhausted through six grills mounted on the ceiling. A seated thermal manikin was placed in the center of the chamber at minimum 5 m distance from the nearest supply diffuser. Each of the supply diffusers was sealed on the side that faced the manikin to prevent interference of supply airflow with buoyant flow induced by the thermal manikin. To minimize other buoyant flows and radiant heat exchange in the chamber, the external wall of the chamber was insulated and lighting fixtures were switched off.

An airflow generator with dimensions 1.8 x 1.0 x 0.2 m (L x W x H) was used to generate a uniform isothermal airflow. The uniformity test was performed at 0.7 and 1 m distance from the outlet of the airflow generator to assure that velocity remains constant at both distances. The test results showed that at both distances the velocity remains fairly constant with a low discrepancy of 10%. More details on the airflow generator can be found in Licina et al. (2014b). The non-breathing thermal manikin with a complex female body shape of 1.23 m height in the sitting posture was used to resemble a real human body. The manikin was dressed in tight-fitted clothing that consisted of t-shirt, trousers, underwear, socks and shoes that corresponded to a typical attire level of building occupants in tropics. The manikin released 65 W/m² of heat which approximates the heat loss from the human body in a comfortable state. Thermal manikin was calibrated before the experiments.

A cough machine was used to approximate the human cough. Liquid used in the cough machine contained a mixture of water (94%) and glycerin (6%) to closely resemble properties of human saliva and its evaporative properties. Such method was previously used in several studies (Chao and Wan, 2006; Pantelic et al. 2009). The mixture of two fluids was discharged through an air-atomizing nozzle that generated puffs of droplets of different size and velocity distribution. By fine adjusting the desired flow rate and pressure of the mixture of air and liquid, the cough machine replicated initial droplet-size distribution reported by Chao et al. (2009) and the velocity of the cough reported by Zhu et al. (2006). It is important to note that number and size of expelled droplets are difficult to be generalized, but rather vary according to the person (Edwards et al. 2004). The temperature of discharged flow was equal to the room air temperature (23 °C) which was lower than the realistic one due to the absence of heating elements.

Aerosol spectrometer (Model Grimm 1.108) was used to measure a real-time aerosol concentration in the breathing zone of the thermal manikin. Previously calibrated aerosol spectrometer with 16 size channels, sampling rate of 1.2 L/min, 1 Hz measurement frequency and reproducibility rate of $\pm 2\%$ was able to count particles in the size range from 0.30 μm to 20.0 μm . For the purpose of this study, we considered pollutant transmission only through particles with aerodynamic diameter range from 0.5 – 0.65 μm . These particles belong to the fine particle range (diameter 0.1 – 2 μm) such as those found in haze/smoke and in most of infectious bacteria. An isokinetic sampling probe was located at the upper lip of the manikin at a distance of 1 cm from the surface, according to the study performed by Melikov and Kaczmarczyk (2007).

Minimized total heat gains in the chamber enabled maintaining a constant room air temperature of 23°C and 60% relative humidity at the minimum ventilation rate (1 h⁻¹). The purpose of the background ventilation was to maintain a constant air temperature in the chamber without creating

disturbance to the manikin's CBL. Disturbance by the ventilation system was assessed by measuring the velocity (Dantec omnidirectional thermal anemometers; accuracy ± 0.02 m/s; ± 0.5 K) at 16 locations around the manikin at 1.2 m distance. The recorded velocity at each point was below 0.05 m/s which indicated that quiescent conditions were achieved (Murakami et al. 2000). The maximum temperature gradient between the point near the floor and the ceiling was less than 0.5 K.

Firstly, the personal exposure was examined in relation to the direction of the invading airflow, i.e. when the manikin was exposed to: (i) assisting airflow from below; (ii) opposing airflow from above; (iii) transverse airflow from front; (iv) transverse airflow from side and (v) transverse airflow from the back. To generate such flows, the airflow generator was positioned in five different positions relative to the manikin, as shown in Figure 1, left (transverse flow from side not shown). Secondly, impact of uniform flow field on the personal exposure was examined for three velocities supplied through the airflow generator: 0.175, 0.30 and 0.425 m/s determined near the surface of an unheated manikin (Licina et al. 2014b). In the experiments when the manikin was heated, the velocities at these locations were modified after collision with the CBL of the heated manikin.

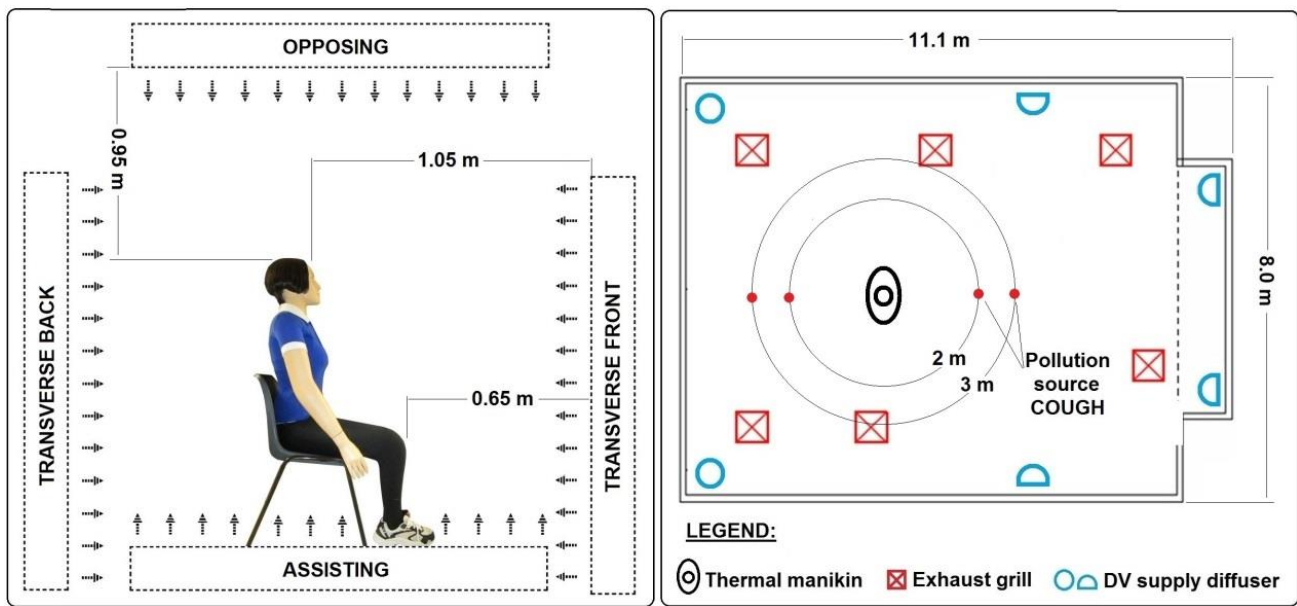


Fig. 1. Experimental design: Invading flow directions (left); the environmental chamber with pollution location (right)

The nozzle of the cough machine was positioned at 2 and 3 m horizontal distance from the manikin's mouth to examine the impact of the distance between coughing and exposed person on personal exposure. In the case when airflow generator was positioned in the front of the manikin, the cough machine was positioned at 2 and 3 m behind the manikin in order to avoid blockage caused by physical presence of the airflow generator (Figure 1, right). In all other cases, the cough machine was positioned in front of the manikin. Total sampling time was 210 s, while the time interval for analyzed data was 150 s. The background concentration was recorded 60 s prior to cough release which was subsequently deducted from the results to minimize measurement inaccuracy due to initial background concentration. The initial background concentration was several orders of magnitude lower than the average concentration of released particles. Measurements were repeated 10 times (one cough every 15 seconds) in each case in order to reduce the bias caused by flow unsteadiness within the human CBL. Measurement uncertainty was accessed based of reproducibility of the results (5%).

3 Results

Figure 2 shows the results of the personal exposure to cough droplets released from 2 m distance from the manikin, as a result of the CBL flow and its interaction with mutually assisting, opposing and transverse flow (from front, back and side). As seen in all cases, the surrounding airflows had a positive or neutral influence on the personal exposure reduction, while the influence of the flow velocity on the personal exposure was dependent on the airflow direction. All the results of the personal exposure of the manikin exposed to invading uniform airflow were compared to the reference case (CBL). Assisting flow around the manikin at the velocity of 0.175 m/s had an ability to disturb and redirect the approaching cough from 2 m distance from front and reduce the cumulative personal exposure by 50%. An increase of the velocity to 0.30 and 0.425 m/s further displaced the cough, reducing the personal exposure to 63 and 70%, respectively. An identical effect on the personal exposure was obtained when the transverse flow from the side was applied. When the manikin was exposed to transverse flow from front and the cough 2 m from the back, the effect on the personal exposure was different. In this case, the head/back of the manikin created an obstacle for the cough droplets which, together with the invading flow from front, further reduced the personal exposure by 75, 82 and 92% for the velocities of 0.175, 0.30 and 0.425 m/s, respectively. It can be observed that in all three airflow directions, increasing the velocity from the airflow generator almost linearly decreased the level of the cumulative personal exposure; however in none of the cases the total exposure reduction was achieved.

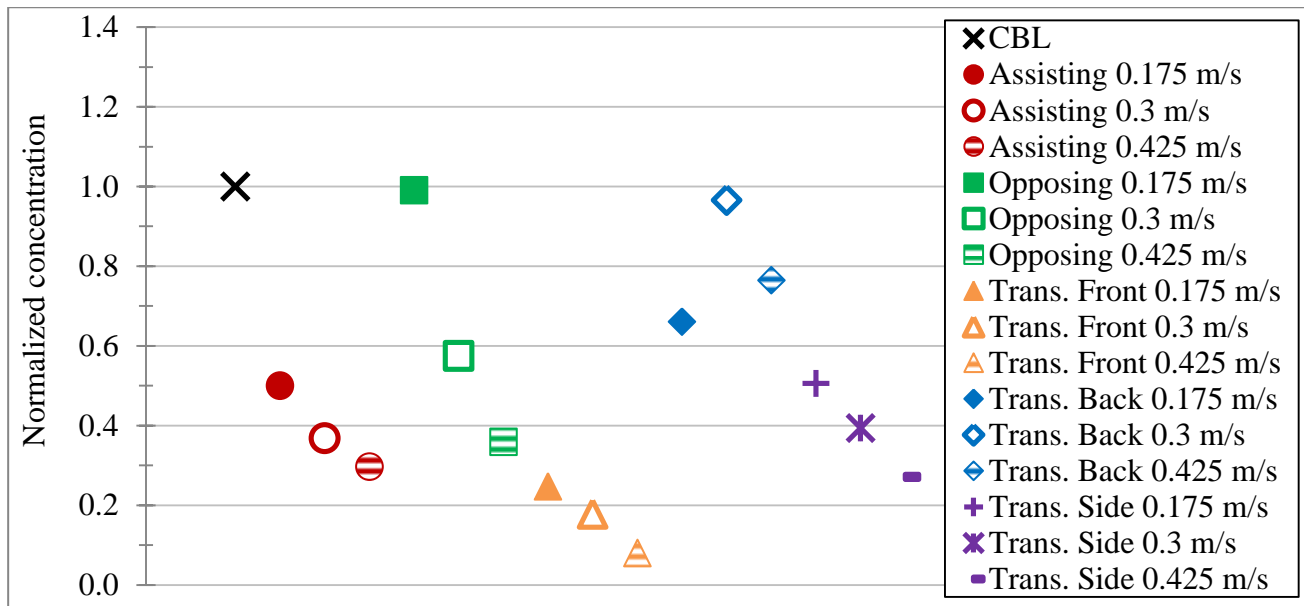


Fig. 2. Normalized cumulative exposure to the cough released from 2 m distance from the manikin - Influence of the CBL, the direction of the invading airflow and the magnitude

Furthermore, the results of the personal exposure of the manikin exposed to the cough from 2 m from the front and the opposing flow from above are presented. Similar to the case when the pollution originated at the feet, the downward flow at the velocity of 0.175 m/s caused negligible reduction in the cumulative exposure. Initial puff released by the cough machine was able to penetrate the breathing zone at the velocity of 0.30 m/s. Upon impingement, however, the downward jet effectively removed the droplets from the breathing zone, thus reducing the cumulative exposure by 42%. Opposing flow at the velocity of 0.425 m/s pushed away part of the cough, which reduced the cumulative exposure by 64%. Finally, when the cough was released 2 m from front of the manikin which was exposed to transverse flow from the back, the velocity had a crucial influence on the exposure. Low velocity at 0.175 m/s was effective in removing the droplets after the

impingement, which resulted in 34% personal exposure reduction. More complex flow structure was created in the breathing zone with the increase of the supply velocity to 0.30 m/s. In this case the cumulative exposure reduction was again negligible. Increasing the velocity to 0.425 m/s partially peeled off the cough jet reducing the cumulative exposure by 23%.

The results of the cumulative exposure of the manikin exposed to the cough released from 3 m distance and the uniform surrounding airflows are shown in Figure 3. In this case, the cough flow was more dispersed and unable to dominate the flow around the manikin, as in the case of 2 m distance. This enabled the surrounding airflows from any direction to substantially reduce the level of personal exposure even at the minimum velocity. Unlike the case of the transverse flow from the back at 0.30 m/s and the cough from 2 m, the cough from 3 m was successfully offset by the same flow reducing the cumulative exposure by 85%. The respective cumulative personal exposure reductions at the velocities of 0.175 and 0.425 m/s were 51 and 88%. Comparing the results from 2 and 3 m releases show the importance of the pollution location relative to the exposed person and the direction of the surrounding airflows. Relatively similar effect on the personal exposure was detected when the uniform surrounding airflow approached the manikin from side, below and above. The transverse flow from front effectively eliminated the invading cough from the back already at the velocity of 0.175 m/s. Further increase of the velocity did not create any effect on the personal exposure.

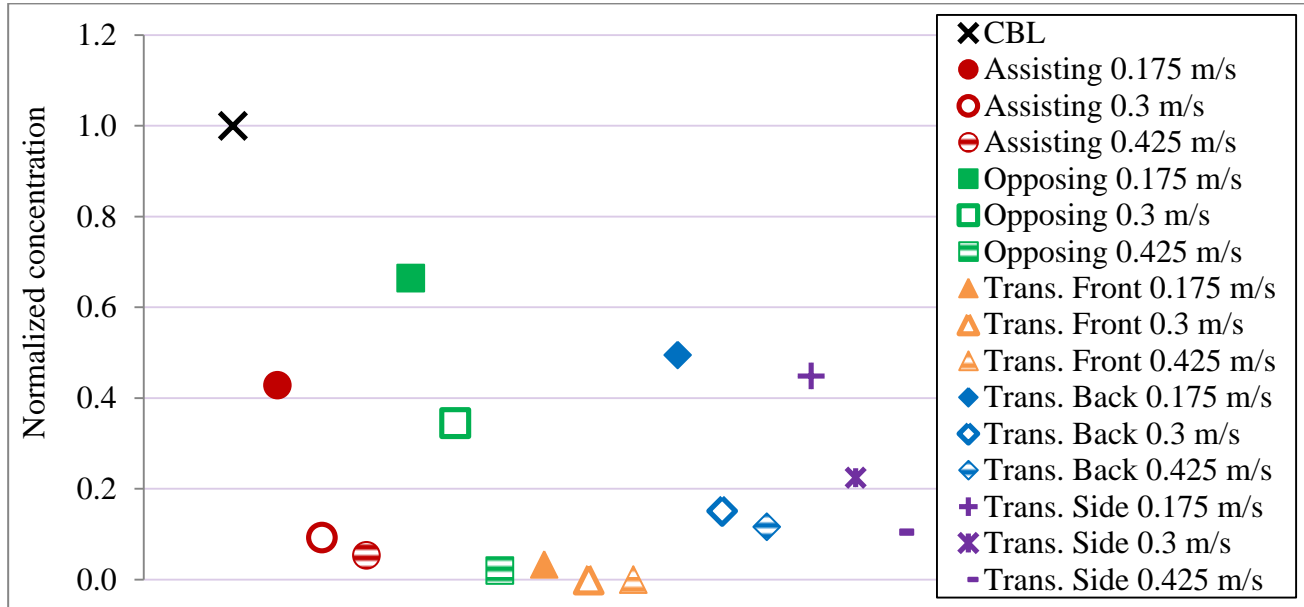


Fig. 3. Normalized concentration of the cough released from 3 m distance from the manikin – Influence of the CBL, the direction of the invading airflow and its magnitude

4 Discussion

The current study is designed to explain fundamental relationship between the personal exposure and air distribution in occupied spaces. The results are discussed in relation to optimal design of different ventilation systems, thermal comfort and energy.

In the current ventilation design, it is commonly accepted that increase of the air supplied to the room reduces the exposure. However, in majority of the cases the room air distribution is not taken into account. The results of this study clearly demonstrate that in some cases, increasing the amount of supplied air does not always reduce the exposure. For instance, flow opposing the CBL at the velocity of 0.175 m/s is unable to reduce the exposure to cough released 2 m from front. Furthermore, in case when the cough is released from 3 m, increasing the velocity of transverse flow from front above 0.175 m/s does not provide additional benefit in terms of the personal exposure.

These results emphasize that there is a non-linear ratio between the personal exposure and amount of the air supplied to the room. From the energy savings perspective, knowing what the optimal supply flow rate is required to minimize the exposure could substantially reduce the energy input. For instance, increasing the velocity of the transverse flow from front from 0.175 to 0.425 m/s would not affect the level of the personal exposure, but the power consumed by fans would increase nearly 15 times. This is because changes in fan power requirements are proportional to the cubed change in speed.

Several existing standards recommend vertically downward ventilation approach as a favorable contaminant removal design that is able to reduce the cross-contamination risk (CDC, 2003; ASHRAE 2013). Examples of such an air distribution are downward diffuse ventilation or downward flow generated by the ceiling mounted fans, chilled beams or personal ventilation supply devices. Findings of this study reveal that at the lower supply velocity, upward ventilation approach performs better in terms of personal exposure reduction, compared to downward approach. A higher discharge velocity of the downward flow of 0.425 m/s reduces the exposure, but it could also cause thermal discomfort (ISO 7730, 2005) and higher energy penalty. In addition, it is important to consider where particles go after being peeled off by the downward flow. If suppressed, they can remain in the lower regions, below the breathing zone, and then accumulate sufficiently with adverse consequences. A relocation of the diffusers from above the occupant to another location that does not directly interfere with the human thermal plume can be recommended. In terms of effective contaminant removal from the room, the assisting flow from below would probably be more preferred strategy than the opposing flow, where the particles can be easily taken above the occupancy zone and then removed or treated. Rooms ventilated with upward piston flow, displacement or under-floor ventilation are typical representatives of such an air distribution. The results of the study suggests that in mechanically ventilated spaces that operate with the low velocity supply, the uniform upward flow from below can be designed to be much more efficient in exposure reduction than the downward flow from the ceiling.

Transverse flows are commonly encountered in naturally/hybrid ventilated spaces where fans are used to enhance comfort of the occupants or in rooms equipped with personalized ventilation, stratum ventilation, etc. Our results show that the transverse flow from the back is less effective in reducing the personal exposure compared to the transverse flow from front or side, when the pollution is released as a cough from 2 m distance. Therefore, when the pollution source approaches from the back, as in case when one person breaths/coughs facing the back of other person (classrooms, offices, transport, etc.), transverse flows from front and side are likely to be the most favorable. The results point out the potential advantages of the personalized ventilation supplied from front and side over other air supply directions, when properly designed. In case of transverse flows, however, it is likely that removed pollution will increase the risk of cross infection of other occupants, since it can easily spread across the room. This issue could be overcome by careful exhaust positioning or by employing personalized exhaust devices (Melikov and Dzhartov, 2013).

The experimental results demonstrate dependency between the personal exposure and factors as pollutant location, airflow direction and the velocity. Although the effect of the CBL shows some impact on the personal exposure, in reality, a person does not keep still and is surrounded by the furniture which disturbs the upward flow of the CBL (Bolashikov et al. 2011; Licina et al. 2014a). It is also important to note that these results pertain only to the sitting posture and temperature, as well as the pollution location. Changes in such factors are likely to modify the level of personal exposure. The effect of a human respiratory cycle should also be taken into account in the future studies. Although each of these topics requires further investigation, several important conclusions can be drawn.

5 Conclusions

This study investigates the personal exposure of an occupant in quiescent indoor environment and when exposed to a uniform velocity field to cough released droplets from a seated infected source. The level of the personal exposure depends on the location of the pollution source, airflow direction relative to the person and relative to the pollutant source and its magnitude. The most favorable airflow patterns are transverse flow from front and side, as they can eliminate the exposure at the minimum velocity; hence, they should be considered in the ventilation design. Increasing the velocity of the transverse flow from the back from 0.175 to 0.30 m/s can increase the level of personal exposure, when the cough is released from 2 m distance. In some cases, increasing the velocity above 0.175 m/s does not provide additional benefit in terms of the personal exposure. Therefore, often there is no a direct correlation between the amount of the supplied air and the personal exposure. Rather than relying on the outdoor air supply airflow as a sole indicator of the indoor air quality, more attention should be paid to better understanding of the room air distribution.

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